The present invention relates in general to an improvement in the vacuum melting, purification and casting of metals and is particularly directed to continuous zone vacuum processing.

In the processing of metals it is well known to employ high temperatures to melt the product so that the metal may be operated upon in various manners, as for the removal of slag therefrom and the casting of the metal into ingots or suitable molds. The more conventional type of casting furnaces are adapted to provide a degree of purification through the rough control of temperatures employed so that those impurities remaining as solvents can be removed, and furthermore, those impurities which naturally float upon the molten metal may be scraped off. Insofar as high level purification is concerned, it has been found that conventional arc furnaces, for example, are quite unsuited for the removal of volatile impurities, inasmuch as it is necessary in this type of furnace to maintain a particular atmosphere in the furnace to support the arc (for heating the metal). There has consequently been developed various types of vacuum furnaces, wherein volatile impurities and occluded gases may be evacuate from the furnace volume as they are evolved from the molten metal being processed.

Vacuum furnaces, as they are known in the art, commonly employ electrical heating means which may, for example, radiate heat to the metal, however, improved versions of vacuum furnaces employ electron beam heating for supplying requisite energy for melting the metal. Electron beam vacuum furnaces have been relatively widely employed in certain fields, particularly in those applications wherein only relatively minute amounts of metal are to be operated upon. In the instance wherein actual production quantities of metal are to be melted, cast, and purified, it has been found that an interrupted zone process is possible by bombarding a metal stock with one or more electron beams and at the same time further bombarding a molten pool of the metal as it drips from the melt stock. The electron energy is thus employed to originally melt the metal and then to add further heat therefor for additional purification of the metal. With relatively high pumping speeds employed in connection with this type of furnace, it is possible to remove a substantial quantity of the gases and vapors evolved from the metal as it is heated and melted. This type of furnace has proven highly advantageous, particularly in connection with refractory metals, wherein it has been found advantageous to attain a very high degree of purification.

As noted above, electron beam vacuum furnaces adapted for quantity melting and casting operations operate by what may be termed an interrupted zone process, wherein the material is fed into one or more electron beams for bombardment heating and melting of the same, and then the metal then drips or streams downwardly in a mold disposed below the melt stock. Within this mold additional heat is applied by electron bombardment to further raise the temperature of the metal and consequently to achieve additional purification thereof. A relatively continuous process is possible in this type of furnace by continually removing the ingot formed in the cooled mold while continuously feeding melt stock into the bombarding electron beam.

Careful consideration of the electron beam vacuum furnace indicates that, although considerable advantage attaches to the utilization of electron beams for heating purposes and to the utilization of high voltage for high quality purification, certain disadvantages are attendant thereto. The present invention is particularly directed to the provision of an improved vacuum furnace utilizing bombardment energy for the addition of heat to metal being processed together with the removal of volatile impurities and insoluble slags throughout processing while at the same time achieving a truly continuous process which is admirably suited to the melting, and purification of both low temperature and high temperature metals. Furthermore, the present invention is particularly directed to the attainment of a much greater degree of purification than is possible in conventional electron beam vacuum furnaces. In this respect it is commonly required for vacuum purification to be repeated a number of times upon the same metal in order to achieve a truly high purity thereof. By the very nature of prior art processes, there is imposed a limitation upon the amount of purification that can be attained in any one single pass through the furnace. The present invention does not suffer from this limitation. Additionally, the process of the present invention and the furnace hereof provides for truly continuous operation together with provision for removal of floating impurities from the processed metal while yet in a liquid state, and a maximized protection for the source of bombardment energy.

In this latter respect it is noted that processing of metals having high vapor pressures of substantial amounts of particular impurities therein cause the evolution of "gas bursts" and highly undesirable splattering in furnaces. These circumstances are extremely detrimental to the maintenance of bombardment sources such as electron guns, for example. Through the provision of vapor barriers and differential pressure zones within the vacuum furnace of the present invention, there is attained a maximized degree of protection for the source of bombardment energy employed herein.

The present invention provides, among other features, for the establishment of a plurality of evacuated zones or regions. Within a first of these regions metal to be operated upon is heated and melted by bombardment and such molten metal then flows through the vacuum furnace of the present invention. The aforementioned first vacuum region is isolated from the remainder of the furnace, and furthermore, the surface of the molten metal therein is likewise retained within the first region so that relatively light weight impurities floating upon the molten metal may be readily removed therefrom in this region. The molten metal then passes through a second evacuated region wherein it is additionally heated by multiple bombardment with elementary particles such as electrons or other charged particles. Continuous and high speed evacuation of this second region provides for removal of volatile impurities arising from the further heated metal flowing therethrough. This second region may be further subdivided into separate vacuum stages. The flowing metal is then directed into such as a water cooled mold or the like for the formation of ingots of desired size or configuration. A third vacuum region of the improved furnace had nothing to do with the bombardment energy. This latter region is maintained at the highest vacuum of any of the regions, and is only connected with the first and second regions aforementioned by minute slots or the like in wall structure defining the third region. In this manner the present invention provides for the attainment of a substantially improved purification of three separate regions of the furnace, i.e. the initial melting region which is separated by a vapor barrier from the remainder of the furnace, an additional heating
region, wherein molten metal flows through an elongated path for multiple bombardment to raise the temperature of the metal required and maintain same for a desired period of time, and a separate highly evacuated region within which there are disposed the bombardment sources such as electron guns for maximum protection of such sources to attain an extended longevity and an improved operation thereof.

Among the additional features of particular note herein is the provision for extensive purification operations in a single pass of material through the furnace. A generally rectangular pool of molten material is established, preferably with an elongated transverse flow of material therefrom so as to afford a maximized area of material and time of processing consistent with large through-put for the furnace. This large area pool is heated and agitated to thereby accomplish maximum removal of occluded gases and volatile impurities without prior art limitations upon available heating time resulting from a dependence on output upon surface area of ingot that is being cast.

The improved vacuum furnace of the present invention is illustrated as to particular preferred embodiments thereof in the accompanying drawings, wherein:

FIGURE 1 is an elevational view in section illustrating one preferred embodiment of the improved vacuum furnace of the present invention; and

FIGURE 2 is a partial plan view in section taken in the plane 2-2 of FIGURE 1;

FIGURE 3 is an elevational view in section of one of the electron guns that may be employed in the furnace of FIGURE 1 and which are therein illustrated in only block form;

FIGURE 4 is a plan view of the same gun illustrated in FIGURE 3;

FIGURE 5 is an elevational view in section of a multiple gun source useful in the furnace of the present invention;

FIGURE 6 is a schematic illustration of the same gun configuration as shown in FIGURE 5 but with the electron beam focus being set forth more particularly;

FIGURE 7 is an elevational view in section of an alternative embodiment of the improved vacuum furnace of the present invention which is particularly adapted to the melting, purification, and casting of high temperature metals;

FIGURE 8 is a transverse sectional view of the furnace hearth with metal therein and additionally illustrating means for sweeping the bombarding electron beams over the surface of the molten metal in the furnace;

FIGURE 9 is a partial plan view in section taken in a vertical longitudinal plane of the hearth and showing an alternative embodiment of the furnace; and

FIGURE 10 is a schematic illustration of a multiple hearth arrangement in accordance with the invention.

Considering the present invention in greater detail, reference is first made to FIGURES 1 and 2 illustrating a preferred embodiment of the vacuum furnace hereof particularly adapted for the melting, purification, and casting of relatively low temperature metals. The furnace comprises a generally rectangular hearth 11 disposed within a vacuum tight housing 12. This hearth may be formed of an outer water cooled shell 13 and an inner high temperature liner 14 with insulating material 16 separating the liner from the shell. Suitable mounting means are provided beneath the shell 13 so that the hearth is disposed horizontally within the vacuum housing 12, as illustrated. The housing 12 is internally divided into three separate regions identified as 17, 18, and 19 in FIGURE 1, and these regions are separated by vapor barriers 21 and 22, described in more detail below. The hearth, above described, extends into both of the separate regions 17 and 18 and provision is made for feeding a melt stock 23 into region 17 above the hearth for melting of the material of the melt stock therein so that the molten material will drip or stream downwardly into the open top of the hearth. These feed and support means for the melt stock may take a wide variety of configurations and there may be employed either vertical, angular, or horizontal feed of the melt stock as desired. There is illustrated in FIGURE 1 a horizontal melt stock feed, wherein the melt stock 23 is disposed upon a water cooled table 24 and is engaged by feed means 25 controllably moving the melt stock further into the region 17 over the region 17 over the region 17, as is described in more detail herein. An upper portion of the melt stock feed forms part of the present invention other than the particular location of same relative to the remainder of the furnace, further details of this portion of the furnace are excluded herefrom.

As noted above, the vacuum housing 12 is divided into three separate regions which are separated by vapor barriers and it is herein further noted that these regions are maintained at different degrees of vacuum. Melting of the melt stock as it is fed over the hearth within the region 17 will cause a substantial evolution of gases and vapors, in addition to the liquid metal and other impurities mixed therewith which may be drawn out of the hearth. The evacuation of the region 17 is accomplished by high speed vacuum pumps, such as illustrated at 31. By the provision of evacuation means having an adequate capacity, there is maintained in the region 17 a substantially vacuum, as of the order of one to twenty microns of mercury, despite the above noted evolution of substantial quantities of gas and vapors during the initial melting of the melt stock. This region 17 is sealed from the other vacuum regions 18 and 19 of the furnace by means of the above noted vapor barrier 21 which extends as a generally vertical wall downwardly from the top of the housing 12 into a pool 33 of liquid metal formed in the hearth by melting of the melt stock. The vapor barrier also extends about the hearth outwardly therefrom to engagement with the side walls and bottom of the housing 12, but has an opening therethrough within the hearth so that liquid metal may flow through the wall of the barrier. A seal is formed by the extension of this vapor barrier wall into the pool 33 and the lower portion of the wall or barrier extending into the pool may be formed of a separate high temperature metal or material, as indicated at 34.

Bombardment of the melt stock to initially melt same in the region 17 is accomplished by the direction of one or more beams of subatomic particles onto the leading edge of the melt stock as it is fed over the hearth. The bombardment beam 36 may, for example, be formed of electrons or ions generated and directed by a source 37 disposed in the vacuum region 19 on the opposite side of the vapor barrier 21 from the region 17. The beam 36 is focused through a small opening 38 in this vapor barrier, and as noted below, minimization of the size of this opening then allows the maintenance of a different pressure on opposite sides of the vapor barrier.

As the melt stock is bombardment heated to drip into the hearth, certain of the impurities in the metal will float thereon in the form of a scum 39. Inasmuch as the lower tip or portion 34 of the vapor barrier 21 extends into the hearth below the top surface of the molten pool of metal 33 therein, it will be appreciated that the floating scum 39 cannot pass along the hearth and is instead retained in the region 17 above the portion of the molten pool of metal therein. Provision is made in the furnace hereof for periodically removing this scum from the top of the molten metal, and means therefore are schematically illustrated at 41 of FIGURE 2. These floating impurities removed by this scum 41 may be swept or pushed from the top of the molten metal by a plunger or the like that may extend exteriorly.
of the housing in vacuum type relation thereto and may, furthermore, be driven by suitable controllable drive means. The scum is pushed from the top of the pool into some type of sump 42 from which it may be drained or otherwise removed from the furnace. The drain pipe 43 shown may be suitable for such removal if the scum is sufficiently fluid, otherwise other means may be employed to remove the solidified scum. As appreciated that this drain pipe 43 is disposed adjacent the bottom of the sump 43 in order that a liquid seal will be maintained therein for preserving the vacuum in the region 17 of the furnace. It is provided in accordance with the present invention that the metal or other material to be operated upon herein shall be initially melted in one vacuum region of the furnace separated from the remainder of the region for vacuum purposes. This molten metal or material is then directed to flow along the open hearth 11 for further heating, so as to additionally volatilize impurities therein, and consequently, to attain an increased purification of the metal. All sources of bombardment energy employed in the present invention are located within the vacuum region 19, which is maintained at the highest vacuum of any portion of the furnace. This region 19 is separated from the initial melting region 17 described above by barrier 21 and removes the remainder of the hearth and other furnace components by the generally horizontal vapor barrier 22 extending longitudinally of the furnace above the hearth. Within the region 19 there are disposed a plurality of beam sources such as, for example, electron beam sources 51 schematically illustrated in FIGURE 1, and each producing at least one electron beam 52 which is focused through a small aperture 53 in the vapor barrier 22. These electron guns may be directed upon the upper surface of the molten metal. The inlet end of the molten metal brought about by the relatively localized bombardment of the upper surface of the molten metal. The inlet end of the hearth may be defined as the end into which initially melted metal drips from the melt stock and the outlet end of the hearth is disposed some distance therefrom along a flow path of molten metal through the hearth and is provided with outlet means for pouring of molten metal into the mold. As illustrated in FIGURE 1, there is provided a funnel or tundish 61 extending from the outlet end of the hearth over a mold 62 into which the molten metal flows. In order to insure flow of molten metal through this spout or tundish, the upper side thereof is left open and an electron beam is directed therein, as illustrated. Furthermore, there is provided for the formation of an electron beam into the open top of the mold 62 so that molten metal flowing from the hearth into the mold is additionally bombarded in the mold itself. This then provides for the maintenance of a molten pool of metal atop a skull in the mold whereby continuous withdrawal of solidified metal from the bottom of the mold may be accomplished. There is illustrated in FIGURE 1 a solidified ingot 63 formed within the mold 62 by solidification of the molten metal flowing therein from the hearth through the tundish 61. This ingot may extend through the bottom of the furnace housing 12, and in practice there is a substantial portion of the upper end of the furnace so that a relatively elongated ingot may be formed in one operation and continuously withdrawn from the furnace as the solidified metal solidifies in the mold. Quite clearly the rate of withdrawal of solidified material must be related to the rate of initial melting of the melt stock and the actual rate of flow of molten metal from the hearth end of the mold. Evacuation of the region 18 encompassing the majority of the hearth wherein purifying bombardment of the molten metal is accomplished, and the ingot casting means at the end of the hearth, may be carried out by high speed evacuation pumps as schematically indicated at 64. The degree of vacuum maintained within the region 18 is intermediate between the extremely high vacuum maintained in the electron gun region 19, and the initial melt region 17 of the furnace. There has been briefly described above an improved vacuum furnace highly suited to the melting, purification, and casting of relatively low temperature metals such as copper. In the instance wherein copper is being operated upon within the furnace hearth, the hearth liner is preferably formed of graphite and will be heated by contact with the molten copper so as to thereby serve to remove oxygen from the molten copper, as for example, by forming of copper with water cooling tubes therein or thereabout while the intermediate insulation 16 between the liner shell may, for example, be formed of porous carbon blocks. The vapor barrier 21 is formed of copper in this instance with a graphite tip 34 thereon, and similarly the other vapor barrier 22 may be likewise formed of copper. Inasmuch as very high temperatures are attained in the furnace, it is preferable to provide for cooling of various means such as the vapor barrier walls, and this may be readily accomplished by attachment of water cooling tubes thereto in heat conducting relationship therewith. Further with regard to the remaining copper, the tundish or tundish 61 is also preferably formed of graphite and there may be employed cold mold casting, wherein the mold 62 is maintained at a sufficiently low temperature for solidification of copper therein as it flows through the tundish from the hearth. It is highly advantageous for the furnace hearth to provide a substantially elongated flow path for the metal being purified in the region 18 of the furnace, in order that purification of the metal may be maximized. This length of flow may be increased by the utilization of graphite dividers 66 extending laterally across the hearth from alternately opposite sides thereof, separating the other side, so as to thereby define a serpentine path for molten metal flow from the inlet end of the hearth to the
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outlet end thereof. As above noted, the melt stock 23 of relatively impure copper is fed into the bombarding beam 36 so as to be heated and melted above the hearth, and consequently, to drip downwardly therefrom and to fill the hearth with a pool or stream of molten copper 35. Atop this internal portion of the hearth between an inlet end thereof and the vapor barrier 21 extending at least in part into the molten stream, there is trapped those impurities in the copper which float thereon, and this is indicated as a secondary flow above the remaining portion of the hearth and casting of copper, it is noted that the rectangular pool of copper established in the hearth has a materially elongated dimension with respect to the depth of the molten metal. Thus, for example, the inner open portion of the hearth may have a dimension of 4 by 6 feet with a molten metal, such as copper, which has a depth of 1 foot. With regard to the graphite dividers in the hearth, it is to be noted that same are only provided for elongating the path of metal from the inlet to outlet ends of the hearth and are not necessary in the carrying out of the present invention, although they do provide an advantage of more strictly confining the path of molten metal flow and at the same time establishing an elongated path of flow for minimizing the overall hearth dimension in relation to the available path length for bombardment during purification.

Provision of bombarding energy in the furnace hereof for the initial melting of material fed therein and the addition of further heat to the molten metal flow as a stream throughout the hearth of the furnace may be accomplished by energetic beams of subatomic particles. Considering the ease of generation and of control, it is advantageous herein to employ either electron beams or ion beams. There is illustrated in FIGURES 3 to 6 certain electron gun configurations highly suited for the present invention and as regard the criteria for the type of beam employed herein, it is of primary importance that it be focused to pass through very small apertures in the vapor barriers of the furnace. Inasmuch as electron beam technology is well advanced and control of energetic electron beams is quite readily accomplished, it is taken here as an example that electron beams shall be employed to provide the bombardment energy in the furnace hereof. Examples of suitable electron beam guns, including operating parameters, are shown and described in greater detail in certain of the patents Nos. 2,963,530 to Hanks issued on Dec. 6, 1960, 2,994,801 to Hanks issued on Aug. 1, 1961, and 3,040,112 to Smith issued on June 19, 1962.

Referring to FIGURE 3, an electron source 71 is schematically illustrated as including an electron emissive filament 72 disposed at least in part within a backing electrode 73 and having an electron accelerating means 74 displaced from the filament. By the passage of suitable current through the filament 72 same will be raised to an electron emissive temperature so that a copious quantity of electrons are emitted therefrom. The electron accelerating means 74 is maintained at a relatively positive potential with respect to the filament and thus attracts emitted electrons as a beam from the source. This source 71 may also be considered to constitute an electron gun, inasmuch as electrons are directionally emitted therefrom in a beam. The electron beam 76, which may correspond to the individual beams 52 of FIGURE 1, will have a certain divergence and there is illustrated two separate electron paths as defining, for example, the envelope of the beam.

It is of major importance in electron beam furnaces that the electron gun be protected from bombardment by positive ions generated within the furnace and also from vapors and the like which might otherwise deposit upon the portions of the gun and deleteriously affect gun operation and even eventually render same inoperable. The furnace hereof is capable of continuous operation and provides a maximum protective cover hereof by the isolation of the gun region 19 from the regions 17 and 18 of the furnace, wherein substantial quantities of gases and vapors may be evolved. Furthermore, the electron gun 71 will be seen to be laterally displaced from the relatively small opening 53 in the horizontal vapor barrier 22. The electron beam 76 is curved and focused to pass through this small opening 53 by means of a magnetic field generated between a pair of pole pieces 81 and 82 by a suitable coil 83 across the ends of these pole pieces. The pole pieces may, for example, be made of iron or the like and have the form of generally flat plates extending upwardly from the top side of the
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vapor barrier 22 toward the electron gun 71 from the coil 83, so that the magnetic field is generated across the top of the opening 53.

In distinction to other types of electron beam focusing, the present invention provides for the direction of the beam into a convex magnetic field, as viewed by the electron gun, and thence into focus substantially at the opening 53. The beam is generated in a region of relatively weak magnetic field and directed through a "barrel-shaped" field in focus at the strongest portion of the magnetic field. This type of beam control provides a lateral compression of the beam, as shown in FIGURE 4, because of the curvature of the field lines and consequent deflection from the applied to the electrons. A maximum focusing effect is achieved in this manner and this is highly desirable in passing the beam through the smallest possible aperture in the vapor barrier. In this manner the physical dimensions of the aperture 53 is maintained at an absolute minimum. The electron beam passing through the aperture 53 will then diverge, as also indicated in FIGURE 3, and consequently will spread in somewhat of a conical shape as it proceeds downwardly from the vapor barrier 22 into impingement upon the upper surface of the molten metal in the hearth.

In this manner then, the present invention provides for maximum protection of the electron guns from spattering metal originating within the hearth region of the furnace. Extremely small apertures are provided through the vapor barriers 21 and 22, and consequently, the possibility of metal vapor dispersing through the apertures is quite small. In addition the large quantity of electrons passing in focus through the apertures 53 minimize the possibility of the vapor continuing upwardly through the apertures without being ionized. The passage of ions through the aperture 53 will be seen to then result in these ions entering a magnetic field which has the proper field strength to deflect electrons through the aperture but insufficient strength to deflect ions back into the electron gun. No possible straight line paths exist between sources of vapor in the furnace and electron guns, for the lateral displacement of the guns from the apertures 53 preclude any such path from existing.

It has been found that very dense electron beams may be desirable and, forgoing momentary extremely minute apertures, as for example, of the order of 54 of an inch square. In order not to provide a low reluctance path shorting out the focusing magnetic field, it is necessary for the vapor barriers 21 and 22 to be formed of a nonmagnetic material such as copper, for example, and it will be appreciated that a structure as shown in FIGURE 5 of vapor passing from the molten metal in the hearth of the furnace will impinge upon these vapor barriers. It is thus advantageous to provide cooling means for the barriers and such is schematically illustrated as cooling tubes 84 on the barrier 22 in FIGURE 3, the tubes being adapted to carry cooling water across the surface of the vapor barrier. These cooling tubes may be disposed above or below the vapor barrier depending upon the dictates of particular design considerations and the, for example, in FIGURE 5 the same cooling tubes are illustrated as being disposed above the vapor barrier in contact therewith.

It is highly advantageous in the present invention to provide very high energy bombardment sources in order to apply desired quantities of energy to the molten metal in the furnace. One manner in which the bombardment energies may be increased is to multiply the number of bombardment sources. One method of accomplishing this result is illustrated in FIGURE 5, wherein it will be seen that there is provided two separate electron guns 91 and 92. The gun 91 is disposed at a greater distance from the center of the magnetic field than is the gun 92, and consequently, electrons emitted from the gun 91 will pass through a weaker field and will thus be curved less by the field so as to traverse orbits of less curvature. This is schematically illustrated by the electron beam envelopes 93 and 94 extending from the apertures of each of the two electron guns 91 and 92, respectively. It will be seen that with appropriate positioning of the guns, electron beams from each will be focused at the aperture 53 in the vapor barrier 22. By the utilization of a number of electron guns and the focusing of beams of each through individual apertures, it is possible in accordance herewith to reduce the requirements for individual guns and yet to attain extremely high energy bombardment.

The electron beam focusing described above, preferably results in the establishment of the beam focus slightly above the vapor barrier 22, rather than directly in the aperture 53 of this barrier. This is illustrated in FIGURE 6, wherein it will be seen that the separate beams 93 and 94 are actually focused at a point immediately above the aperture 53. The representation of FIGURE 6 is included only for the purpose of precluding misunderstanding of the beam focusing, for in practice it is found that the focal point of the beam or beams is only slightly displaced above the vapor barrier and that consequently the minute physical dimensions of the barrier aperture 53 are yet attainable.

There has been described above a preferred embodiment of the present invention particularly adaptable to the melting, purification, and casting of relatively low temperature metals or the types commonly encountered in industry today. There was set forth an example of furnace operation upon copper, however, it is not intended by this example or the above description and illustration to limit the present invention to conventional metals. Quite to the contrary, the inventors hereof is equally well suited to the melting, casting, and purification of all types of metals including not only iron and nickel-base alloys, but also very high temperature metals, which are often times termed refractory metals. Within this group of high temperature metals are found those elements which have extremely high melting points so as to approximate the characteristics of relatively well known refractories. Examples of these types of metals include columbium, hafnium, tantalum, titanium, zirconium, and tungsten. While the general concepts of the present invention are equally applicable to all types of metals, it will be appreciated that certain physical variations of furnace structure are desirable and, in fact, necessary for the containment of those metals which are only molten at temperatures in the thousands of degrees or which react with typical container materials such as oxides. There is illustrated in FIGURE 7 a variation of the present invention particularly adapted for utilization with refractory metals.

As illustrated of vertical wall 109, the furnace of this invention includes an elongated generally rectangular hearth 101, formed in this instance of a material such as copper and including cooling means such as the water passages 102 illustrated therethrough. This elongated hearth or open topped container 101 is mounted by suitable footing within a vacuum housing 103. In common with the above described embodiment of the present invention, the furnace of FIGURE 7 is illustrated to be divided into three separate vacuum regions. The first region 104 is evacuated by suitable pumping means 106 and encompasses the initial melting operation of a melt stock 107 fed over the hearth 101. The initial melt stock 107 may be fed vertically or horizontally into an electron beam 108 for initial melting of the melt stock so that same drips downwardly into the hearth.

The vapor barrier in the form of a generally vertical wall 109 separates the vacuum region 104 from the remainder of the furnace. This wall extends from the top of the furnace downwardly into the hearth 101 and also surrounds the hearth both on the sides and bottom so as to substantially completely isolate the initial vacuum region 104 from the remainder of the furnace. Within the hearth 101 there is disposed a molten high temperature metal resulting from the melting of the melt stock 107, and owing to the substantial cooling of the
hearth 101 there will then be formed a solidified layer 111 of metal along the bottom and walls of the hearth. Continuous addition of heat by electron or other bombardment may also be formed of material such as copper with water cooling therein, as indicated by the beam 108, serves to maintain a thin sheet or film of molten metal at the top of the hearth above the solidified metal 111 therein. This molten metal 112 flows longitudinally through the hearth from the input end to an output end. The vapor barrier 109, which may also be formed of material such as copper with water cooling therein, as indicated, extends into the molten sheet of metal 112, and consequently, will be formed a solidified portion of metal 113 about the end or tip of this barrier extending into the molten metal, as indicated.

On the opposite side of the barrier 109 from the input end of the hearth there is defined a second vacuum region 116 about the hearth, and this region is separated by a generally horizontal vapor barrier 117 from an upper gas region 118 of the furnace. Molten metal flowing as a sheet from the outlet along the hearth 101 toward the outlet end thereof is bombarded by electron beams 121 directed onto the upper surface of this metal. This additional electron bombardment serves to overcome heat losses and to further heat the metal and to raise same to an extremely high temperature for added removal of volatile impurities therein. The application of copious quantities of heat to the molten metal sheet 112 and the removal of heat from the bottom of this flowing sheet of metal will then be seen to establish very substantial thermal gradients in the metal so that same is rather vigorously stirred in its passage along the hearth. This is highly advantageous in enhancing the removal of impurities from the metal.

At the outlet end of the hearth there is formed a water cooled spout or tundish 122 through which molten metal flows from the hearth to drip downwardly into a water cooled mold 123. High speed evacuation means 124 serve to continuously evacuate the vacuum region 116 of the furnace so as to maintain a very substantial vacuum within this portion of the furnace and to insure the rapid removal of gases and vapors evolved from the extremely high temperature molten metal being processed therein. Cooling of the mold 123 serves to solidify metal dripped therein from the hearth. Heat is applied to the upper surface of this metal dripping into the mold so as to maintain a molten pool of metal within the mold above the ingot. In much the same manner as discussed above, this molten metal maintained atop the ingot 126 as it solidifies serves to prevent the occurrence of voids or density irregularities in the ingot. By the continuous bombardment of the upper surface of the spout or tundish 122 through which the molten metal flows from the hearth, it is insured that such metal will remain molten in the tundish.

In much the same manner as previously described, the furnace embodiment of FIGURE 7 provides an extremely high vacuum region 118 within which there is disposed the bombardment sources 131. One of these sources directs a beam of subatomic particles 108 through the vapor barrier 109 for initially melting the melt stock 107, and also for applying added heat to the metal within the hearth at the entrance end of the hearth. A plurality of the bombardment sources 131 direct beams downwardly through small openings in the generally horizontal vapor barrier 117 so as to thus bombard the upper surface of the molten metal sheet 112 flowing along the hearth. This application of additional heat serves, as previously stated, to further purify the metal being processed. Certain other bombardment sources 131 also disposed within the high vacuum region 118 direct beams downwardly through openings in the vapor barrier 117 to insure the maintenance of a molten pool atop the solidifying ingot 126, and also to insure the continuous flow of molten metal through the outlet 122 of the furnace. These bombardment sources 131 may, for example, comprise the electron gun configuration and focusing means illustrated in FIGURES 3 and 4 and described above. Also it is noted that suitable high speed evacuation means 132 communicate with the high vacuum region 118 of the furnace in order to maintain the extreme vacuum desired therein, and in this respect such vacuum may again be established and maintained at an order of 0.02 to 0.2 microns of mercury.

The embodiment of the present invention illustrated in FIGURE 7 is, as above noted, particularly adapted for operation upon iron and nickel-base alloys and high temperature metals, and it is found that with only a very thin sheet or film of molten metal 112 continuously flowing through the furnace hereof it is possible to purify these refractory metals to such an extent that only a pass of same through the furnace is necessary to attain resultant metals of a purity hitherto substantially unknown. In particular, it is noted that the continuous processing hereof, wherein the molten metal is subjected to repeated heating to very high temperatures, accomplishes in a simplified manner results which have previously only been possible through the repeated passage of metals through high temperature vacuum furnaces. It is known in the art that original melting in a vacuum furnace employing electron beam heating is highly advantageous, and it has furthermore been developed that remelting of refractory metals is normally required if high purities are to be obtained. This is of substantial importance in many fields of modern technology, wherein the true chemical properties of refractory metals are of extreme importance. The presence of even a few parts per million of contaminant in certain metals will very materially alter the physical characteristics of such metals, thus making them wholly unsuited for certain applications. On the other hand, the sufficient minimization of the percentage of impurities, such as oxygen for example, in many refractory metals then opens many new possibilities for manufacturing processes and high temperature elements hitherto unavailable. The vacuum furnace hereof affords means for attaining extreme degrees of purification in a continuous process requiring only one passage of the metal through the furnace.

In addition to the foregoing, it is noted that the division of the furnace hereof into separate portions by the vapor barriers within the furnace serves to minimize the difficulties attendant the separate separations performed in these individual regions. The very substantial vapor and gas evolution occurring in the initial portion 104 of the furnace is prevented from entering other portions of the furnace to thereby limit the purification or damage the electron guns, for example, utilized in providing bombardment energy. The separation of these processes from the region of gas and vapor evolution during metal purification, as is accomplished by the generally horizontal vapor barrier 117, serves to materially enhance the operation of these sources and to provide for a substantial increase in the longevity thereof. Prior art difficulties with respect to electron beam bombardment, for example, is almost entirely overcome by the present invention.

It is to be appreciated that a wide latitude of variations and alternatives are possible in carrying out the present invention. Thus, for example, it may be desirable under certain circumstances to vary the physical configuration of the bombarding beam adjacent the hearth of the furnace, or alternatively to move or sweep these beams over the surface of the metal within the furnace. A number of different procedures are possible in this respect and there is illustrated, as exemplary only, the provision of magnetic beam sweeping in FIGURE 8. This beam sweeping over the hearth of the furnace of FIGURE 7 in cross section, illustrates the provision of magnetic pole pieces 152 extending upwardly alongside of the hearth. These pole pieces extend beneath the hearth to opposite ends of a magnetic coil 153, which upon suitable energization will pass a magnetic flux through the pole pieces and then across the top of the hearth. By energizing this coil 153 with a
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13 varying current there will be produced a magnetic field between the pole pieces above the hearth which varies in intensity and may even vary in direction as desired. Such a varying magnetic field existing in the path of the beams 121 directed downwardly onto the molten metal in the hearth will deflect the beams a varying amount. Consequently, it will be seen to be possible to sweep the beams as desired and thereby control the energization of the magnetic coil 153.

The present invention, as described above in connection with a number of different embodiments thereof, may be varied in numerous ways to suit particular design considerations or to vary certain structural features thereof. The mounting of the hearth, for example, may be accomplished in the variety of ways, and the physical positioning of the vacuum housing of the furnace may be varied, particularly with respect to the provision of space for withdrawing a substantially elongated ingot of metal from one end thereof. Thus, the housing itself may be at ground level and a trench or depression formed to accommodate lowering of the ingot from the furnace, or alternatively the furnace itself may be mounted in a raised position above the floor of a building or the like so that adequate clearance is provided beneath the housing for removal of the ingot. It is to be further noted that various electrical systems may be utilized in the furnace of the present invention are not illustrated herein, inasmuch as generally conventional circuitry may be employed therein. It is believed apparent that power supplies of considerable output capacity must be available for the purpose of energizing the bombardment sources employed in the furnace. Additionally there must be provided for the energization of magnetic coils for guidance and focusing of the beams as well as suitable pumping and piping for removal of heat, as described above. The vacuum pumping must be carried out at a very substantial level in order to maintain vacuum conditions within the housing and the particular region into which it is divided, particularly when it is considered that very substantial quantities of gases and vapors may be evolved in at least certain portions of the vacuum housing.

In addition to the division of the vacuum furnace into three separate vacuum regions, it is also possible to provide for flow of molten material through a plurality of separate vacuum regions. There is illustrated in FIGURE 9 a portion of a vacuum wherein molten material 33 flows through a plurality of separately evacuated regions during processing of this material. Employing the same system of numerals as in FIGURE 1, the vacuum furnace of FIGURE 9 includes the hearth 11 with a vertically oriented bar 21 in a region 17 from the remainder of the flow path of molten material within the furnace. Vertical walls or baffles 66 disposed in part across the hearth provide for establishing a serpentine flow path for the molten material, and at least some of these walls extend upwardly and outwardly to form vapor barriers 66. These walls extend about the hearth as does bar 21 and each of these is provided with openings therethrough below the upper surface of the molten material 33 flowing through the furnace. The reaction or purification region in path 18 is divided into separate portions indicated at 18 and 18' with each of the regions having separate evacuation ports 151. With this structure, there is provided for separate evacuation of consecutive reaction or purification regions through which the molten material 33 flows, and consequently, there may beintroducta a greater number of regions along the flow path in order to maximize purification of the molten material. It is to be appreciated that the illustration of FIGURE 9 only relates to the establishment of successive separated vacuum regions along the flow path and does not attempt to show all elements of a complete furnace, reference being made to FIGURES 1 and 7 in this respect.

For extremely large furnaces, particular advantage is to be found in the provision of a plurality of hearths through which molten material passes in traverse from an initial melting region to a mold into which the purified material is solidified. As above noted, elongation of the flow path and maximization of the surface of molten material is highly advantageous in achieving very high degrees of purification. In the instance wherein very large quantities of material are to be processed in accordance herewith, the provision of successive hearths through which the molten material flows without interruption removes certain difficulties of construction and the like otherwise associated therewith. A multiple hearth arrangement is schematically illustrated in FIGURE 10 wherein there are shown three successive hearths 11a, 11b, and 11c connected by tundishes 61a and 61b and directing ultimately purified materials through a final tundish outlet 61c into a mold 62. Although the schematic illustration of FIGURE 10 is not intended to depict details of the furnace, it is noted that one or more vacuum housings 12 are provided in enclosing relationship to the hearths and, of course, suitable evacuation means are provided for establishing a high vacuum within such enclosure. Separate portions of the over-all housing 12 may be separately evacuated and separated from successive portions as indicated, for example, by the dashed lines in FIGURE 10 and in accordance with the above description of the present invention. Thus, the region about the initial hearth 11a is divided into separate portions by vapor barriers such as illustrated and described in connection with FIGURE 1 of the drawings heretofore, and the regions about the further hearths 11b and 11c may be divided into separate vacuum regions by the barriers such as discussed above in connection with the illustration of FIGURE 9. As above noted, the utilization of a plurality of hearths comprising a single elongated flow path is particularly desirable in very large furnace installations, however, the various embodiments and alternatives of the present invention described herein and those variations apparent to those skilled in the art may be combined in any desired manner to accommodate varying circumstances or to overcome particular problems in connection with the purification and casting of alternative materials in varying quantities.

While the present invention has been described above in connection with particular preferred embodiments thereof, it is not intended to limit the scope of the invention to the terms of the description nor to the exact details of the illustration, and instead reference is made to the claims for a precise delineation of the true scope of this invention.

What is claimed is:

1. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw raw material in said melting point in said first chamber and for maintaining a molten pool of said in said hearth in said first chamber, second electron beam generating means for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.
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2. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, a generally upright transverse wall positioned intermediate the ends of said hearth dividing said enclosure into a first pressure chamber and a second pressure chamber, said wall including a tip portion extending into the molten pool of metal in said hearth to a position below the normal level of the pool and above the hearth bottom there, by defining an opening for passage of molten metal from the first chamber to the second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

3. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure an opening, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool in said hearth allowing for passage of molten metal from said first chamber into said second chamber, means extending into the molten pool and transversely of said hearth for preventing float impurities from traveling along said hearth, sweeping means disposed to move across the top of the molten pool to remove floating impurities therefrom, means for removing the floating impurities from the furnace, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means for heating said molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

4. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said enclosure having a transverse wall wherein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool in said hearth allowing for passage of molten metal from said first chamber into said second chamber, said transverse wall being provided with at least one slit at a point above the normal level of the molten pool in said hearth to allow passage of an electron beam therethrough, generally horizontally disposed wall in said transverse wall in said hearth and said slit in said transverse wall defining with said enclosure and said transverse wall an electron gun chamber, said horizontal wall being provided with at least one slit to allow passage of an electron beam therethrough, first electron beam generating means in said electron gun chamber for directing a beam of electrons through said slit in said transverse wall onto a quantity of raw materials in said first chamber for heating the raw materials above their melting point, and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means in said electron gun chamber for directing at least one beam of electrons through said slit in said horizontal wall for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said chambers within said enclosure, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

5. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, said transverse wall being provided with at least one slit at a point above the normal level of the molten pool in said hearth to allow passage of an electron beam therethrough, generally horizontally disposed wall in said transverse wall in said hearth and said slit in said transverse wall defining with said enclosure and said transverse wall an electron gun chamber, said horizontal wall being provided with at least one slit to allow passage of an electron beam therethrough, first electron beam generating means in said electron gun chamber for directing a beam of electrons through said slit in said transverse wall onto a quantity of raw materials in said first chamber for heating the raw materials above their melting point, and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means in said electron gun chamber for directing at least one beam of electrons through said slit in said horizontal wall for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber for removing gases and vapors evolved therein, means for evacuating said second chamber to a lower absolute pressure than said first chamber to remove vapors evolved therein, and means for evacuating said electron gun chamber to a lower absolute pressure than said second chamber, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

6. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool in said hearth allowing for passage of molten metal from said first chamber into said second chamber, said transverse wall being provided with at least one slit at a point above the normal level of the molten pool in said hearth to allow passage of an electron beam therethrough, generally horizontally disposed wall in said transverse wall in said hearth and said slit in said transverse wall defining with said enclosure and said transverse wall an electron gun chamber, said horizontal wall being provided with at least one slit to allow passage of an electron beam therethrough, first electron beam generating means in said electron gun chamber for directing a beam of electrons through said slit in said transverse wall onto a quantity of raw materials in said first chamber for heating the raw materials above their melting point, and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means in said electron gun chamber for directing at least one beam of electrons through said slit in said horizontal wall for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber for removing gases and vapors evolved therein, means for evacuating said second chamber to a lower absolute pressure than said first chamber to remove vapors evolved therein, and means for evacuating said electron gun chamber to a lower absolute pressure than said second chamber, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.
beam generating means in said electron gun chamber for directing a beam of electrons through said slit in said transverse wall onto a quantity of raw materials in said first chamber for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means in said electron gun chamber for directing at least one beam of electrons through said slit in said horizontal wall for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber to a pressure of not more than 20 microns of mercury, means for evacuating said electron gun chamber to a pressure of not more than 0.02 micron of mercury and means for evacuating said second chamber to a pressure intermediate the pressures in said first and electron gun chambers, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

7. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and forming a molten pool thereof, said hearth including a high temperature graphite liner separated from a surrounding cooled shell by heat insulation, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

8. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal and for forming a molten pool thereof, said hearth comprising a open-topped continuously cooled container in which a portion of the molten metal solidifies to form a skull therein with a thin sheet of molten metal thereon, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said first chamber, additional electron beam generating means for heating the molten pool of metal in said second chamber, means for evacuating said first chamber to remove vapors evolved therein, means for separately evacuating each of said additional pressure chambers, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

9. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal defining an elongated flow path of large surface area from an inlet end to an outlet end, said hearth having a large width and length relative to depth and having a plurality of upstanding extending laterally inward from opposite walls thereof substantially but not completely across said hearth to define an elongated serpentine flow path for the molten metal in said hearth, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said first chamber, second electron beam generating means for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said outlet end of said hearth for withdrawal from said enclosure.

10. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal defining an elongated flow path of large surface area from an inlet end to an outlet end, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, at least one additional transverse wall intermediate the ends of said hearth in said second chamber which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said first chamber, additional electron beam generating means for heating the molten pool of metal in said second chamber, means for evacuating said first chamber to remove vapors evolved therein, means for separately evacuating each of said additional pressure chambers, first electron beam generating means for heating raw materials above their melting point in said first chamber and for heating the molten pool of metal in said hearth in said second chamber, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said hearth for withdrawal from the furnace.

11. A high vacuum furnace for the production of highly purified metal comprising an enclosure, an elongated horizontally disposed hearth within said enclosure for receiving molten metal defining an elongated flow path of large surface area from an inlet end to an outlet end, said enclosure having a transverse wall therein intermediate the ends of said hearth which forms with the walls of said enclosure, said hearth, and the molten pool of metal in said hearth a pressure barrier thereby dividing said enclosure into a first pressure chamber and a second
pressure chamber, said transverse wall in the region within said hearth terminating at a point spaced above the bottom of said hearth and adjacent the surface of the molten pool thereby defining an opening for passage of molten metal from said first chamber into said second chamber, first electron beam generating means for heating raw materials above their melting point in said first chamber above their melting point and for heating the molten pool of metal in said hearth in said first chamber, additional electron beam generating means for heating the molten pool of metal in said hearth in said second chamber, said means directing said beam of electrons onto separate limited areas of the surface of the flowing molten metal in the pool for uneven heating thereof to produce thermal gradients therein providing thermal stirring of the molten pool, means for evacuating said first chamber and said second chamber to remove volatilized impurities, and means adapted to receive the purified metal from said outlet end of said hearth for withdrawal from said enclosure.

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